RAYLEIGH-TAYLOR MIX EXPERIMENT ON PEGASUS

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Abstract

The Rayleigh-Taylor Mix (RTMIX) project will attempt to diagnose and understand the growth of a mixing layer at the interface between an imploding metal liner and a polystyrene foam core in a series of pulsed power experiments on the Pegasus capacitor bank. Understanding the effects of material strength will be an important part of the study. During the initial phase of the implosion, the liner/foam interface is Rayleigh-Taylor (RT) stable; however, as the foam is compressed, it decelerates the liner causing it to bounce and to go RT unstable. In this paper, we report 1D and 2D MHD simulations and preliminary results from the first experiment in the series.

One-Dimensional Simulations

RAVEN, a 1D Lagrangian magnetohydrodynamics (MHD) code with the capability to model the coupling between a lumped driving circuit (Pegasus) and a dynamic MHD mesh (the RTMIX liner assembly), was used to investigate and establish the basic design. The RTM-1 liner was a thin-walled composite cylinder with 200 μm of OFHC Cu inside 800 μm of 1100 Al. The liner had a 0.8-cm inner radius and a 2-cm height. The liner surrounds a very uniform, high-density (0.524 g/cm^3), open-cell, polystyrene foam with voids of ~1 μm in diameter. At a charge voltage of 42 kV, Pegasus produced a peak current of 5.4 MA with a quarter-cycle rise time of ~7 μs.

Figure 1 displays the baseline RAVEN simulation for the 1D dynamics of RTM-1. The liner is predicted to bounce 6.5 μs after the appearance of current in the load. The resulting pressure profile in the foam appears to be a unique signature of the bounce as well as an indirect measure of the quality of the implosion. Several diagnostic development efforts are dedicated to measuring this pressure, and will be reported elsewhere. Based on previous experience and careful 2D MHD design simulations, we expected the 1D character of the implosion to persist at least through the bounce. The combination of reflections and axial motion induced at the glide planes, magnetic RT instabilities on the outer diameter of the liner (especially at the liner/glide plane contact point), and hydrodynamic instabilities on the inner diameter of the liner eventually result in 2D and 3D distortions of the liner followed by complete liner disintegration. As discussed later, the dynamic radial X-radiograph taken at 8.6 μs indicates that the liner is still intact after the bounce, and confirms the predicted 2D distortions that are beginning to develop near the glide planes.

Estimations of Mixing Width due to RT Instabilities

Classical Rayleigh-Taylor theory[1] states that an accelerated interface between fluids of different densities is RT unstable when the direction of the acceleration, g, is in the direction from light to heavy. Ignoring the effects of strength, this occurs in the RTM-1 experiment when the dense liner's implosion velocity is impeded by the less dense foam. Two regimes of RT growth are discussed below, the linear regime and the turbulent regime. In the linear regime, we assume that a sine wave perturbation on an interface, with amplitude a_0 and wavenumber k, will grow as $a_0 \exp(\gamma t)$, where the growth rate, γ, is given by, $\gamma^2 = kAg$, and A is the Atwood number. As a result of linear growth, the amplitude of the instability eventually grows to be comparable to the wavelength. Continued non-linear growth and mode coupling are expected to cause the bubbles and spikes to mix turbulently. Simple scaling theory, supported by planar experiments and direct numerical simulations, suggests that the resulting turbulent mixing width

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14. ABSTRACT
The Rayleigh-Taylor Mix (RTMIX) project will attempt to diagnose and understand the growth of a mixing layer at the interface between an imploding metal liner and a polystyrene foam core in a series of pulsed power experiments on the Pegasus capacitor bank. Understanding the effects of material strength will bean important part of the study. During the initial phase of the implosion, the liner/foam interface is Rayleigh-Taylor (RT) stable; however, as the foam is compressed, it decelerates the liner causing it to bounce and to go RT unstable. In this paper, we report 1D and 2D MHD simulations and preliminary results from the first experiment in the series.

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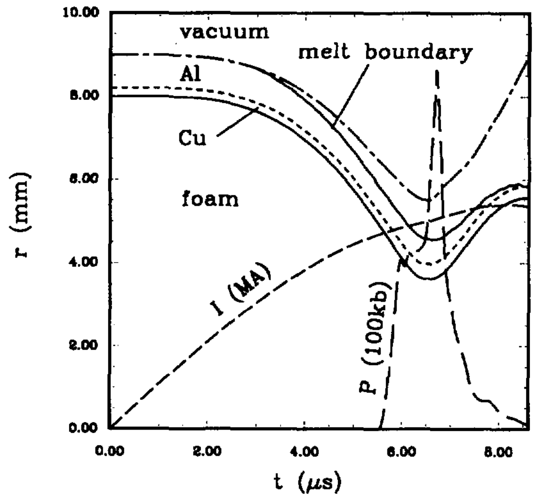

Figure 1: One-Dimensional RAVEN simulation of RTM-1 experiment.

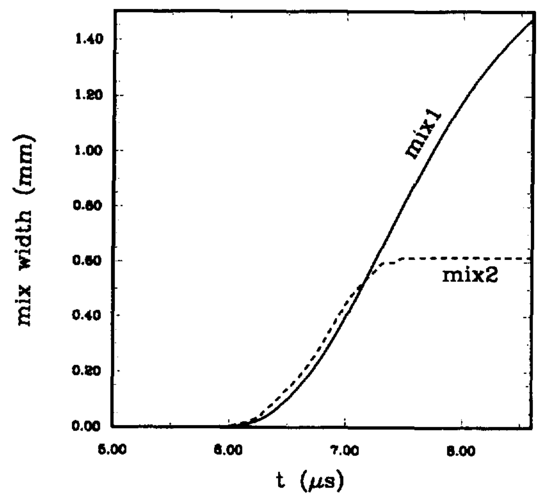

Figure 2: Estimation of mixing width in the absence of material strength.

should grow as $\Delta r = \alpha A g t^2$. For values of A >0.6, reasonable, though not universally accepted values of α are 0.2-0.3 for the heavy fluid mixing into the light fluid and 0.06 for the light mixing into the heavy.[2] This expression for the mixing width is only valid when A and g are constant and greater than zero. However, in the RTMIX experiments, neither of these conditions are met. With no proof, and no attempt at a justification, two expressions for the turbulent width, which acknowledge the time dependent behavior of A and g and reduce to the simple growth expression for constant A and g, are,

$$\text{mix1:} \quad \Delta r = 2\alpha \iint Agdt'\,dt'', \qquad \text{and} \qquad \text{mix2:} \quad \Delta r = \alpha\left[\int \sqrt{Ag}\,dt'\right]^2.$$

For mix1, the integration is not started until the interface first goes unstable. Note that when Ag <0, mix1 allows for the possibility of demixing. In mix2, Ag is reset to zero any time Ag <0; therefore, mix2 does not allow for demixing. Dimonte[3] has shown data from the linear electric motor experiments which is not inconsistent with mix2, and Winske[4] has shown consistent behavior in the plasma regime. A heuristic derivation of mix2 is given by Shvarts *et. al.* [5]

If strength were unimportant, applying mix1 and mix2 to the 1D RAVEN simulation in Fig. 1, would give qualitative estimates of the mixing width which might be expected in RTM-1. These estimates are shown in Fig. 2, where, we have arbitrarily used α =0.2. However, as seen in Fig. 1, RAVEN predicts that the copper does not melt until well after the bounce. If material strength suppresses RT growth, then no mixing would be expected.

For the case of a plastically deforming solid, Drucker,[6] and Robinson and Swegle,[7,8] suggest that the RT growth of the amplitude of a perturbation can be described by,

$$\frac{d^2a}{dt^2} = kAga - \frac{4kY}{\sqrt{3}\rho(1+e^{-kh})}, \tag{1}$$

where Y is the yield strength and h is related to the liner thickness. If we assume (1) to be applicable for this experiment, we can set the right hand side to zero and solve for the minimum amplitude, a_c, that we expect to grow,

$$a_c = \frac{4Y}{\sqrt{3}\rho Ag(1+e^{-kh})}. \tag{2}$$

Figure 3 shows a_c from the RAVEN simulation with $(1+e^{-kh})$ set to one, indicating that an amplitude greater than ~25 μm is unstable, while anything less than ~25 μm will not grow. Given the 1D behavior of the RTM-1 2D simulations, we did not expect a perturbation of more than 25 μm; and therefore, we expected no mixing. However, if a large perturbation were imposed, or did develop for whatever reason (flaw in the liner, asymmetry in the implosion, bleed-through of magnetic RT perturbations from the outside, etc. ...), it is possible to estimate the growth that might be expected by approximating the solution for (1) as,

$$a(t) = a_0 e^{\int_0^t \sqrt{kAg}dt'} - \int_0^t dt' \int_0^{t'} dt'' \frac{4kY}{\sqrt{3}\rho(1+e^{-kh})}. \tag{3}$$

For example, in the case of an initial 50 μm amplitude, 1 mm wavelength perturbation, (3) can be numerically integrated using parameters form the 1D RAVEN calculation; the result is displayed in Fig. 4. Note that the exponential term in (3) dominates while the stabilizing term, which only grows as t^2, makes very little contribution. The linear growth phase should saturate and the mix layer begin to grow turbulently long before the 100-fold growth to 5 mm plotted in Fig. 4. We plan to test this hypothesis by imposing an unstable perturbation on the inner diameter of the copper for the next experiment, RTM-2.

Complicating Issues

The problem of understanding mixing at an interface is certainly not limited to understanding Rayleigh-Taylor instabilities, even if we could understand the linear, non-linear, and turbulent phases, including transitions between them. In the previous section, we heuristically looked at the complications introduced by material strength in the linear growth phase. Other issues that we have not addressed, which could contribute to mixing in the RTMIX experiments, are discussed briefly below.

Richtmeyer-Meshkov instability: Shocks traversing a density discontinuity (interface) which is perturbed, will cause growth of the perturbation. In the RTM-1 experiment, the main source of shocks is reflections in the central foam.

Kelvin-Helmholz instability: Shear flow at an interface will cause mixing of adjacent materials. On the other hand, shear flow tends to suppress RT instabilities.[9] At least through the bounce in RTM-1, there should be very little shear flow (by design) at the boundary between the copper and the foam.

Bell-Plessett instability: In convergent geometries, an imploding shell will tend to "crinkle" on its inner surface. In the RTMIX experiments, we have only a 2:1 convergence which should minimize the effect of crinkling.

Surface Condition: In the RTM-1 experiment, complicating surface phenomena like ejecta, spall, and microjet formation, should be minimized by the shockless drive of the smoothly rising Pegasus current. There is no initial shock from a liner/target collision, but this does not imply that shocks are not present as a result of liner motion.

Experimental Description and Results

Figure 5 shows the assembly drawing for the load region of the experiment. In order to keep the liner dynamics as one-dimensional as possible (i.e., minimal axial motion), the top and bottom of the foam cylinder are tamped with massive tungsten glide planes. The two glide planes are assembled so that the distance between the glide plane/liner contact points is 2 cm. The glide plane angle is 16 degrees from the outer radius of 8 mm into the predicted turn-around radius of 4 mm. Inside of 4 mm, the glide plane angle is zero (see Fig. 7a on the last page for annotations which illustrate the geometry). Based on results of 2D MHD simulations, which will be discussed below, the foam cylinder is designed to fit snugly against the zero-degree flat face of the glide planes, but to leave a gap from 4 mm to 8 mm. The

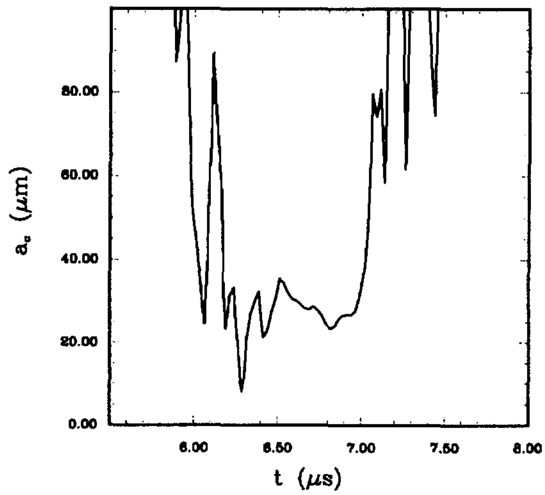

Figure 3: Critical amplitude for RT growth from Eq. 2 and RAVEN simulation.

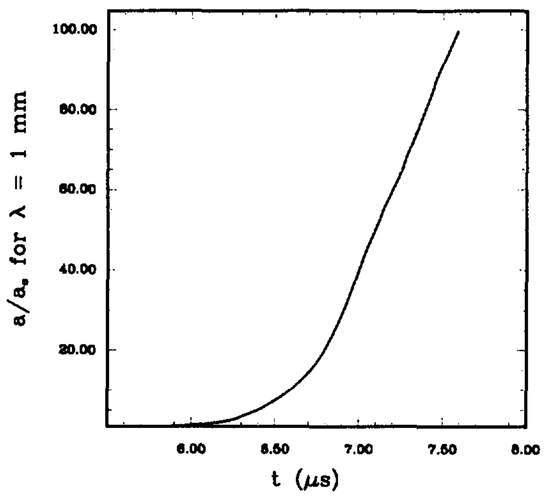

Figure 4: Results of Eq. 3 with a_o =50 μm and λ = 1 mm using RAVEN simulation.

8-degree angle of the foam, which leaves the gap between the foam and the glide plane (see Fig. 7a), was chosen to give a smoother (more one-dimensional) liner implosion in the 2D MHD simulations, especially at the contact point between the liner and the glide plane. Each tungsten piece, made of a machinable, high-density alloy, HD-18, has a 5-mm diameter diagnostic hole drilled on-axis to within 2 mm of the flat face of the glide plane. *Pressure diagnostics, are placed inside the holes.*

Pegasus was fired at a nominal voltage of 42 kV. The measured bank performance, and the predictions from the 1D RAVEN calculation, are shown in Fig. 6. Note that the predicted and measured current are almost indistinguishable. The sharp feature in the dI/dt traces at 6.5 μs is associated with liner bounce; the curve with the sharpest feature is from the 1D simulation. Excellent agreement between the 1D simulation and the faraday rotation data for the current and the current derivative support the validity of the predicted quasi one-dimensional behavior of the liner.

2D MHD Simulations and Results

Extensive 2D MHD calculations were conducted to provide input into four specific areas. They were: 1) glide plane design, 2) diagnostic placement, 3) liner design, and 4) prediction of the range of hydrodynamic conditions affecting instability growth in the load region.

Figure 7a shows the simulation geometry for the final 2D design for RTM-1. The predicted density profiles at 6.5 μs and 8.5 μs are shown in Figs. 7b and 7c. Figure 8 shows reconstructions from the x-radiographs at similar times. A qualitative comparison of the simulations in Figs. 1 and 7 with the radiographs in Fig. 8 shows that we model the liner dynamics quite well. Furthermore, as predicted, the liner definitely undergoes an unstable phase as it bounces, and the liner is still intact at 8.6 μs.

Some deviation from quasi one-dimensional behavior is obvious at late times in the both the 2D simulation and the radiograph. Magnetic RT instability growth is evident in the melted and partially vaporized aluminum on the outer diameter of the liner, especially in the corners near the glide planes; however, little effect from bleed-through to the copper/foam interface can be seen. Preliminary analysis of the original radiographs (and high resolution digital images as well) shows no evidence of RT mixing at the copper/foam interface, consistent with the simple analytic analysis. Recall from Fig. 1 that the copper is not predicted to melt. The “no mix” conclusion is not obvious from the low resolution reproductions in Fig. 8. More complete analysis of the radiographs, taking into account resolution, blur, and background noise, will be required to quantify the “no mix” conclusion.

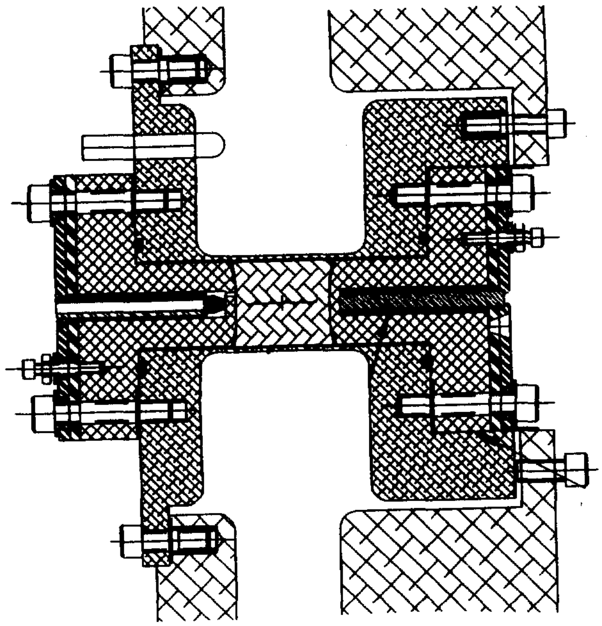

Figure 5: Assembly drawing of load region for RTM-1 experiment.

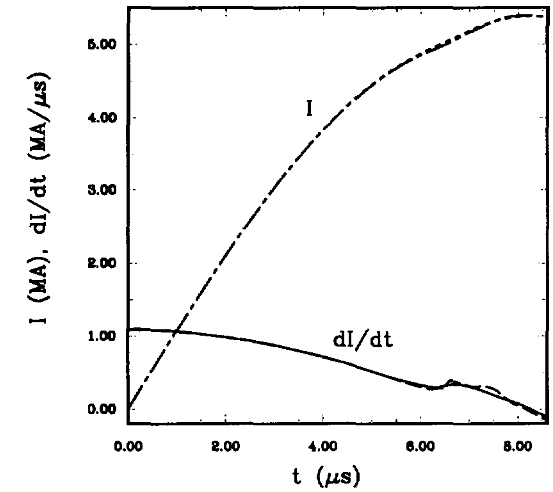

Figure 6: Comparison of RAVEN simulation and faraday rotation measurement.

The density profiles as well as the radiographs illustrate the need for tungsten glide planes. These pictures show a significant deformation of the glide planes on axis caused by the pressure in the foam. Any glide plane material lighter than tungsten would allow axial release of the foam compression and drastically reduce the achievable pressure and the desired symmetry.

Conclusions

The RTM-1 experiment was the first in a series of RT mixing experiments. Preliminary analysis of the radiographs suggests that material strength inhibited mixing at the copper/foam interface over the timescale of this experiment, as predicted by simple analytic models and 1D and 2D MHD simulations. Furthermore, the radiographs confirm that the liner is stable enough to conduct mix experiments; and that magnetic RT instabilities, which grow in from the outer diameter in the aluminum driver, did not seem to bleed through to the inner diameter. In the next experiment, we will test growth of a seeded RT instability in the presence of strength. Future experiments will attempt to study RT growth in a similar geometry in the absence of strength.

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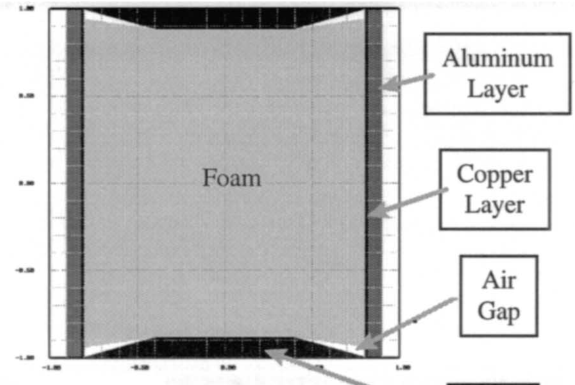

Figure 7a. Time = 0.00 µsec

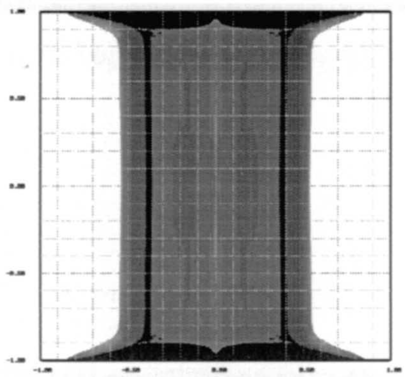

Figure 7b. Time = 6.50 µsec

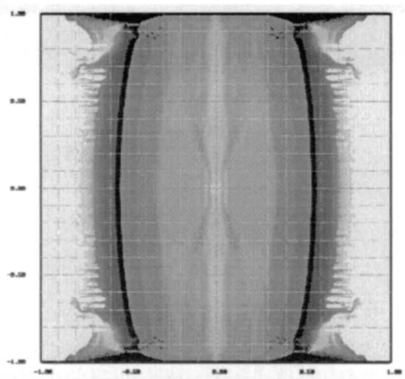

Figure 7c. Time = 8.50 µsec

Figure 7. Calculations

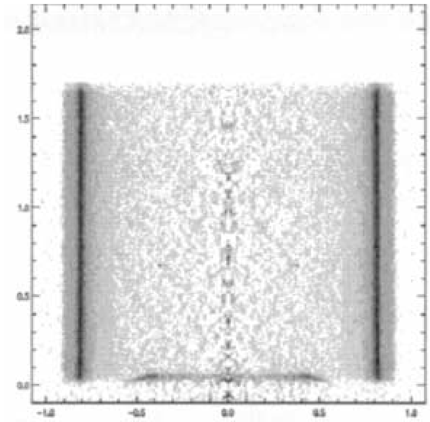

Figure 8a. Static (Time = 0.00 µsec)

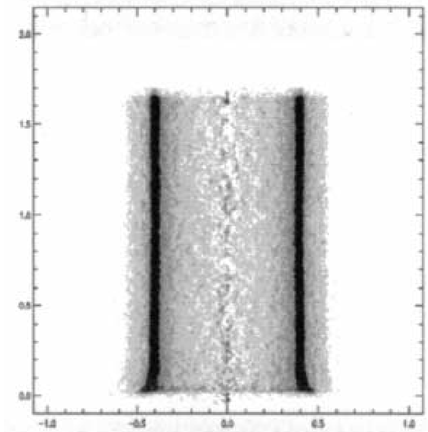

Figure 8b. Time = 6.50 µsec

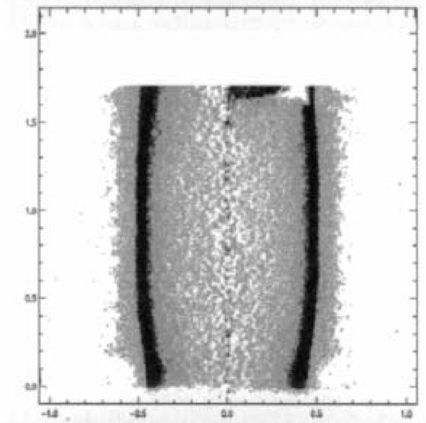

Figure 8c. Time = 8.60 µsec

Figure 8. Reconstructed Cross-Section from Radiograms